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PROGRESS REPORT ON STUDIES ON THE DESIGN OF STABLE CHANNELS BY THE BUREAU OF RECLAMATION

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PROGRESS REPORT ON STUDIES ON THE DESIGN OF STABLE CHANNELS BY THE BUREAU OF RECLAMATION

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Introduction

Since January 1950, the Bureau of Reclamation has conducted a program to investigate new and improved methods in the design of unlined canals. Particular emphasis has been given to methods of obtaining a rational solution to the problem of sediment movement as it relates to design of unlined canals.

This paper summarizes the results of the investigation up to about June 1952. In general, the principal progress made in these studies has been along three general lines: (1) the clarification of the general principles of stable channel design, the knowledge of which has long been in an unsatisfactory state, (2) the working out of a tentative method of designing unlined earth canals to insure freedom from scour, and (3) the development of an analysis of the channel shape for certain conditions involving minimum excavation quantities. It has so far been impossible to study many important aspects of the general problem, especially that involving the design of canals transporting considerable coarse sediment. It is believed, however, that considerable improvement in design procedure has been accomplished, and that a better understanding of the general problem has been gained, so that greater progress in working out future developments will be possible.

In studying the general principles of stable canal design, an intensive study of the literature on this subject from all over the world has been made. It has been found that the subject is a very complex one, and that a great variety of conditions exists which makes the best solution in many cases differ widely from those where other conditions prevail. A complete solution of the problem must therefore include an analysis of all these conditions and a determination of the solution applicable to each. The first part of this paper outlines the fundamental principles involved in the design of stable channels and the range of conditions encountered. The second part of the paper covers the principles involved in the protection of canals against scour from the flowing water. It presents the quantitative relations developed, and illustrates their application to canal design. The third part deals with the development of an analysis of the channel shapes for canals involving minimum excavation quantities

General Aspects of Stable Channel Design

Definitions and First Principles

Since the term "stable channels" as used in this report has a rather special meaning, it is desirable to define the term and explain its limitations.

A "stable channel," as used in this paper, is an unlined earth channel for carrying water, the banks and bed of which are not scoured by the moving water, and in which objectionable deposits of sediment do not occur. Sediment has been defined as[1] "Fragmental material transported by, suspended in, or deposited by water or air, or accumulated in beds by other natural agents; any detrital accumulation, such as loess." This report is concerned only with the sediment aspects of earth channel design, and deals with stability of the channel only from the standpoint of the movement or deposition of earth materials by the flowing water. It does not deal with the stability of the banks from sloughing or sliding down into the canal. The latter is a problem in soil mechanics, for which the principles have been to a large extent developed.

Three Classes of Unstable Channels

From the standpoint of stable channels, as defined in this report, there are three classes of unstable channels: (1) channels where the banks and/or bed are scoured without objectionable deposits being formed, (2) channels in which objectionable sediment deposits occur without scour being produced, and (3) channels in which scour and objectionable deposits are both present[2].

With sediment-free water only the first class of instability can occur. The first class of instability (scour without deposit) can also occur from water carrying sediment, especially when the amount of sediment carried by the water is small.

The second class of instability (deposit without scour), can only occur from the sediment brought into the canal with the flowing water or scoured from the banks and bed of a channel farther upstream. A common case is a lined canal or one cut through a scour-resistant material, into which large quantities of coarse sediment enter with the inflowing water.

The third class of instability usually occurs when water containing large quantities of coarse sediment is introduced into a canal, the bank and bed of which are composed of material which has low-scour resistance.

For prevention of instability of the first class, an analysis of scouring action only is necessary. For prevention of instability of the second class, it usually is necessary to insure that the sediment brought into the canal at its upstream end is carried out at the downstream end. The basic analysis of this problem must therefore be from the approach of sediment transportation. The presentation of instability of the third class involves the analysis of the combination of the scour and transportation problems.

General Aspects of Sediment Transportation in Canals.

Every canal, when flowing at its design discharge, has a definite maximum capacity to carry sediment of a certain size range. If more of the material of this size range is fed into it, deposits will occur. If less than this amount is fed in, it will be transported on down the canal. In regions where the sediment loads carried by the streams are large, canals are frequently supplied with more sediment than they will carry and harmful deposits result. Where the streams carry light sediment loads, the condition where canals receive less than they can carry is more frequent and sediment troubles are usually

[1] Transactions, American Geophysical Union, Vol.28, December 1947, p. 936.
[2] Since this paper was written, it has been discovered that these three classifications have been previously pointed out by A. R. Thomas in the 1945 Annual Report of the Central Board of Irrigation of India.

of a minor nature. In India and Pakistan, where the sediment loads are usually high, the first condition is encountered in some localities, but in most cases in this country, the second condition exists and trouble from sediment deposition is not so important.

To understand these conditions more clearly, consider a canal of uniform slope and cross section carrying a uniform flow of clear water, with a non-erodible bed and banks. Assume that a small quantity of sediment, of a small enough size to be readily moved, is fed into the upper end of this canal at a uniform rate. After sufficient time has elapsed for equilibrium to be obtained, this material will be continuously moved down the canal and out at the lower end, at the same rate as it is introduced at the upper end. Under these conditions, small patches of the material will form on the bed of the canal, from which particles are alternately moved away or deposited as the velocity fluctuates, due to turbulence. Suppose that the rate at which the sediment is added is increased. After equilibrium for this new rate is established, the sediment will be discharged out of the canal at its lower end at this new rate. Under this condition, there will also be patches of sediment on the bed of the canal, from which the sediment will be alternately picked up and deposited, but in this case, the area covered by these patches will be greater than in the former case. In both cases, the area will be such that the turbulent currents will just move along the canal the amount of material introduced at the upper end. This will also be the case for still further increase in rate of introduction, until the patches cover the entire bottom of the canal. When this point is reached, the turbulence cannot pick up anymore sediment and move it along, and the amount carried out at the lower end of the canal is the maximum possible amount of movement under these conditions. If material is introduced into the upper end of the canal at a still greater rate than this maximum transportation rate, sediment will be deposited in the canal, at a rate equal to the difference between the introduction rate and the maximum transportation rate. One of the most important problems of design of stable channels carrying sediment therefore involves the determination of the hydraulic factors for a canal which will have a transporting capacity sufficient to carry the material introduced at the upper end.

History of the Development of Stable Channel Science

The science of stable channel design has been developing over a long period, and the literature on it is very extensive. The most extensive work has been done in India and Pakistan, where the world's most extensive modern irrigation works are located. Some work has also been done in Egypt, the United States, and a number of other countries. Much of this literature has been investigated in connection with this study, but as only the scour aspects of the problem have been investigated in detail, it has not been possible yet to review thoroughly all of the literature dealing with the other cases.

Unfortunately, the limitations of space do not permit the publication of the review of the literature[3] which was prepared in connection with this study. Those who are interested in persuing this subject further will also find the reviews of Inglis[4] and of Malhotra and Ahuja[5] of value.

[3] Progress Report on Results of Studies on Design of Stable Channels U. S. Bureau of Reclamation Hydraulic Laboratory Report No. Hyd.- 352.

[4] "Historical Note on Empirical Equations Developed by Engineers in India for Flow of Water and Sand in Alluvial Channels," Sir Claude Inglis, Proceedings International Association of Hydraulic Research 1948, pp. 93-106.

[5] "A Review of Progress on Theory and Design of Stable Channels in Alluvium," S.L. Malhotra and P. R. Ahuja. United Nations (ECAFE) Technical Conference on Flood Control, New Delhi, 1951.

Forces Causing Scour on Canal Banks and Bed

The first step in analyzing the problem of securing freedom from scour in canals appears to be a consideration of the forces causing such scour.

Scour on the banks and bed of a canal takes place when the particles composing the sides and bottom are acted upon by forces sufficient to cause them to move. As pointed out in the report on the earlier studies of this Bureau in stable channels,[6] when a particle is resting on a level bottom of a canal, the force acting to cause motion is that due to the motion of the water past the particle. If scour is to be prevented, this motion must not be rapid enough to produce forces on the particle sufficiently large to cause it to move. If a particle is on a sloping side of a canal, it is acted on, not only by the water, but also by the force of gravity, which tends to make it roll or slide down this slope. The force tending to cause the downward motion is the component, in the direction of the slope, of the force of gravity acting on the particle. If the resultant of the force due to the motion of the water, and the component of the force of gravity acting on the particle, is large enough, the particle will move. Where cohesion of the particles is present, for the particles to be moved, the forces acting must be sufficient to overcome this also.

Tractive Force Distribution on Sides and Bed of a Canal

The movement of material on the banks and bed of a canal, where cohesion is is not present, depends upon the steepness of the side slope and the velocity and turbulence near the banks and bed. The forces due to the slope of the sides are easily designated, but those due to the velocity and turbulence near the boundaries are difficult to determine, due to the high rate of change of velocity with distance above the bed and the rapid fluctuations of velocity due to the turbulence in the flowing water. Another complicating factor is the presence of the boundary layer. The possibility of reaching a satisfactory analysis from a study of the velocities acting on the particles, therefore, did not seem promising and instead the approach from the standpoint of tractive force or shear was adopted.

Briefly stated, tractive force or shear is the force which the water exerts on the periphery of a channel due to the motion of the water, and it acts in the direction of flow, not normal to the surface, as does the static water pressure. It is not the force on a single particle but rather the force exerted over a certain area of the bed or banks. This concept was first introduced into hydraulic literature by M. P. du Boys[7].

The shear or tractive force is equal to and in the opposite direction from the force which the bed exerts on the flowing water. If no force was exerted by the banks or bed on the water, it would continue to accelerate, just as a frictionless ball rolling down an inclined plane. In a uniform channel of constant slope, in which the water is moving in a state of steady, uniform flow, the water is not accelerating because the force tending to prevent motion is equal to the force causing motion. The tractive force under these conditions is therefore equal to the force tending to cause the water to move. This force is the component, in the direction of flow, of the weight of the water. In a

[6] "Stable Channels in Erodible Material," E. W. Lane, Transactions ASCE. Vol. 102, 1937, p. 134.

[7] du Boys, M. P., "The Rhone and Streams with Movable Beds," "Annals des Pontes et Chaussees, Tome XVIII, 1879.

channel of infinite width and length with uniform slope, the tractive force exerted by the water on a square foot of area is the component in the direction of flow of the weight of the water above that square foot. The weight of this water is equal to wD where w is the unit weight of the water and D is the depth of flow. The component of this weight in the direction of flow is this weight multiplied by the slope, S, or wDS. As will be shown later, in most canals of the shape used in irrigation, the tractive force near the middle of the bottom very closely approaches that in an infinitely wide channel or to this value wDS.

In trapezoidal channels, such as are commonly used in hydraulic engineering work, the tractive force acting is not uniformly distributed over the bed and banks, and in analyzing scour in canals on the basis of tractive force, it is therefore necessary to determine how this force is distributed. In this study a condition of similitude of tractive force distribution in canal cross sections has been assumed. Under this assumption, in all canals having the same ratio of B to D and the same side slopes, the tractive force distribution will be similar, that is, the tractive force at any point in one cross section will be similar to that in any other point with the corresponding position in any other similar section. Thus, if we can get the tractive force distribution in any canal, we will have the distribution in any other canal of similar cross section. The foregoing discussion has dealt with trapezoidal channels, but it can be applied also to other shapes of channels.

The Use of Tractive Force in Canal Design

The concept of tractive force or shear has been widely used in recent years in fluid mechanics and has been extensively employed in studying sediment movement, but in the United States it has seldom been employed in earth canal design. In Europe it seems to have been more widely used for this purpose. Schoklitsch suggested the use of tractive force as the basis of canal design, stating that it was not possible to give fixed and definite values of the maximum tractive forces, for different soils, but that the following values in pounds per square foot could serve as a basis of design: earth, 0.062; loam, 0.102; sand, 0.082; stony and loamy soil; coarse gravel, 0.205; very compact soil, 0.256. The use of shear in canal design was suggested by Williamson[8], but no extensive study of the limiting value for safe design seems to have been made.

Evidence Supporting Tractive Force Analysis

One of the advantages of the use of the tractive force analysis rather than the limiting velocity approach for the design of large canals is that it indicates why higher velocities are safer in large canals than in small ones. This fact that higher velocities can be used in large canals has been known for many years. In his book Working Data for Irrigation Engineers--1915, Moritz states "It is a well-known fact that small canals erode at a lower mean velocity than large canals." In their paper on "Permissible Canal Velocities"[9] Fortier and Scobey also indicate this fact and include a correction for its effect. Ivan E. Houk in his discussion of this paper also brings out the

[8] Proc. Inst. of Civil Engineers, Vol. 229, 1929-30 pp. 349-352.

[9] "Permissible Canal Velocities," Fortier and Scobey, Transactions ASCE, Vol. 89, 1926, pp. 940-984.

increase in scouring velocity with depth. In a USSR article[10], the variation of limiting velocity with depth is given on Tables 6 and 8 which agrees so closely with that which would be produced by a constant value of tractive force that it seems possible that the corrections were derived from this assumption. A table of canal dimensions based on extensive experience of Bureau personnle was recently drawn up for use in design of canals in earth on the Columbia Basin Project. When studied on the basis of tractive force analysis, they showed nearly constant values of tractive force, where the conditions were constant. Limitations of space prevent a detailed discussion of this subject, but the available information strongly supports the claim of superiority of the use of limiting tractive force over limiting velocity as a basis for canal design.

Determination of Tractive Force Distribution from Velocity Distribution

Studies to determine the distribution of the tractive force or shear on the bottom and sides of canals were carried on along two lines. One was based on an analysis of the measured velocity distribution in such channels. The other was a mathematical approach, assuming a power law of velocity distribution. The velocity and shear distribution was worked out mathematically for simple cases, and for more involved cases by a membrane analogy and the method of finite differences, as described in more detail in the following paragraphs.

An attempt was made to determine the distribution of shear or tractive force on the perimeter of canals from published data on the velocity distribution in trapezoidal channels, All available data on trapezoidal shapes (including the special cases of rectangular and triangular shapes) were used. The method used was that probably first developed by J. B. Leighly[11]. Unfortunately the data available were not sufficiently exact nor of sufficient quantity to provide an adequate solution by this method. The results scattered widely, and in the range of shapes in which canals ordinarily occur it was not possible to determine the shear distribution with sufficient certainty to justify its use.

The Analytical Approach to Shear Distribution

An attempt was made to work out the shear distribution by a mathematical process using the logarithmic distribution of Von Karman and the boundary layer theory, but this was not found to be practicable. It was found possible, however, to handle mathematical solutions for a velocity distribution in which the velocity is any power of the distance from the bottom.

Mathematical solutions were worked out for rectangular channels with bed width-depth ratios of 2:1. The distribution for a bed width-depth ratio of 2:1 also gave the distribution of a 90° triangular channel. It was not found feasible to use mathematical solutions for the ordinary forms of trapezoidal channels, and it was therefore necessary to resort to a membrane analogy. In order to check the reliability of this device, solutions were also made on it of several of the forms solved by mathematical analysis. Solutions were also made for several cases by means of the method of finite differences, which

[10] "The Maximum Permissible Mean Velocities in Open Channels," Gidrotekhnicheskoye Stroitelstvo, 1936.

[11] "Toward a Theory of the Morphologic Significance of Turbulence in the Flow of Water in Streams," J. B. Leighly, University of California Publications in Geography, Vol. 6, 1932, pp. 1-22.

were also checked by comparisons with the mathematical solution. Unfortunately, space is not available to give an adequate discussion of this study. Those who are interested in it are referred to the detailed report covering this work[12]. The results of these studies of shear distribution are given in Table 1. In this table the tractive forces at the different points on the perimeter are given in terms of wSD. In terms of the maximum shears on the sides and bottom of the section, which are the values needed for canal design, the results are given in Figures 1 and 2. It is believed that the results of these studies give the most reliable information on shear distribution which is available at the present time. These results indicate that for trapezoidal channels of the shapes ordinarily used in canals, the maximum shear on the bottom would be close to the value wSD and on the sides the maximum is close to 0.76 wSD.

Limiting Tractive Forces for Noncohesive Materials

Probable the most important factor in the design of clear water canals in coarse noncohesive material is the limiting tractive force which the various types of materials will stand.

Except for the previously mentioned suggestions of Williamson and Schoklitsch, an extensive search of literature disclosed no suggested limiting values for canal design. A great deal of information was found, however, on the tractive forces which would start the motion of noncohesive material of various sizes. This material was thoroughly studied and summarized[9], but limitations of space prevent its being discussed here. As will be mentioned later, the critical tractive force which will just start motion is not necessarily the same as the limiting or permissible tractive force which can be used in canal design, especially for the sand size materials.

San Luis Valley Determinations of Limiting Tractive Forces

Since the data on limiting tractive forces, for coarse, noncohesive material were very meager, observations were made on canals in the San Luis Valley of Colorado. Laboratory studies of critical tractive force have usually been performed with particles of a small size range, but canals in coarse, noncohesive material are usually constructed in a material containing a large range of sizes. The experiments in the San Luis Valley canals not only provided information from prototype canals, but also gave insight into the stability of canals built in graded materials. Space is available here only for a brief summary of these studies[13].

The canals experimented upon are located where the Rio Grande leaves the mountains in Colorado and flows out onto an alluvial cone. The material composing this cone decreases in size from the apex outward, and provided canals in material of a wide range of sizes. The canals were stable, very straight and regular in section, and were steep enough to give high velocities and tractive forces. In general, they furnished an unusually complete opportunity

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[12] "Sedimentation studies in open channels--Boundary shear and velocity distribution by membrane analogy, analytical and finite difference methods," Olsen and Florey, Bureau of Reclamation Laboratory Report No. Sp. 34.

[13] "Some Factors Affecting the Stability of Canals Constructed in Coarse Granular Materials," E. W. Lane and E. J. Carlson, Report on Meeting of International Association of Hydraulic Research, Minneapolis Meeting 1953.

for experimentation.

It was expected that the water in flowing down these canals at high tractive forces would remove all of the material below a certain size and that this size would be indicated in the mechanical analysis of the material on the canal beds. This would be the size moved by the tractive force which had acted in these canals. However, this expectation was not realized, as the smaller particles were shielded by the larger ones and a critical size could not be determined.

The tractive forces acting in these canals were therefore compared with the composition of the material through which the canals were constructed, as determined by samples taken from borrow pits at the various sites. The size used in the comparison was that size of which 25 percent of the weight of the material was larger. The tractive force used was that resulting from the maximum sustained flow which had recently occurred in the canal, as nearly as could be determined from the flow records.

Fifteen reaches of canal were used, having discharges ranging from 17 to 1,500 second feet and slopes from 4.2 to 51 feet per mile. The results of the measurements are summarized in Figure 3, on which is plotted the tractive force determined from the sustained flow against the 25 percent greater size. The discussion of the results and their application to limiting tractive forces for design purposes will be taken up later in this paper.

The Effect of Side Slopes on Limiting Tractive Force

The effect of side slopes on limiting tractive force has been developed, by considering the forces acting on a particle on the sides of the canal, as previously pointed out. These forces are, (1) the force of the water, tending to move the particle down the canal in the direction of the flow, and (2) the force of gravity, tending to move the particle down the sloping side of the canal. By combining the two actions, the effect of the slope of the sides on the critical tractive force necessary to cause motion can be evaluated.

For convenience in design, the effect of side slopes was worked up[14] into a factor, K, which is the ratio of the tractive force required to start motion on the sloping sides, to that required, in the same material, to start motion on a level surface.

This ratio involves only the angle of side slopes of the canal and the angle of repose of the material and is expressed by the following formula:

$$K = \cos \phi \sqrt{1 - \frac{\tan^2\phi}{\tan^2\theta}}$$

where:

K= the ratio of the tractive force necessary to start motion on the sloping side of a canal, to that required to start motion for the same material on a level surface,

θ=the angle (with the horizontal) of repose of the material,

ϕ=the angle (with the horizontal) of the side slope of the canal.

For convenience in solving this equation, Figure 4 has been prepared. For

[1] "Critical Tractive Forces on Channel Side Slopes in Coarse, Noncohesive Material," Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-366.

example, in a material whose angle of repose was 30°, the critical tractive force which would move material on the side of a canal with 2:1 side slopes would be 0.44 times that which would cause motion on a level surface.

Studies of Angle of Repose of Noncohesive Material

As previously pointed out, the stability of the side slopes of a canal in noncohesive material involves the angle of repose of the material. A study was therefore made of this subject, beginning with a thorough review of all available literature on it. This was followed by a limited amount of laboratory investigations and observations on a large number of stock piles of various-size material at gravel-washing plants.

The results of the studies made in the laboratory are given in Figure 5. The experiments showed that a considerable range of values could be obtained in repetitive tests, but time was not available to make a sufficient number of observations to obtain accurate average values, and the determinations made, therefore, are subject to considerable scatter. The results showed that for the larger sizes, the angles were not materially different for the various conditions of stacking in air or water, but for the sand sizes these had more effect. The average results of all observations of the angle of repose of stock piles at gravel-washing plants are also given on this figure.

Although these data indicate that the angle of repose increases with both size and angularity, the data scatter widely and are insufficient in number to closely determine any quantitative relations.

For use in design, until more exact relations can be determined, Figure 6 was drawn up, giving values of the angle of repose for material above 0.2 inch in diameter for various degrees of roundness. In this diagram the angles of repose have been somewhat arbitrarily limited to a maximum value for very angular material of 41° and very rounded material of 39°. This was believed necessary to secure conservative designs because of the lack of data on angles of repose of the larger size material.

Hydraulic Roughness of Canals in Noncohesive Material

Measurements of flow of water in channels have demonstrated that the hydraulic roughness of canals in coarse, noncohesive material changes appreciably with the size of material involved. In designing canals in such material, it is therefore important that this be considered if correct predictions of the canal discharge capacity are to be obtained. It is equally important that the slopes be accurately estimated if reliable values are to be obtained of the tractive force which will act on the sides and bottom of the channel. In order to secure more reliable design of stable channels in such material, a study was therefore made of the relation of hydraulic roughness to particle size of canal material. The first step in this study consisted of a review of all available literature on this subject. The data from the experiments carried out by this Bureau on the flow in the canals of the San Luis Valley were also included. These studies showed that the hydraulic roughness of canals, as expressed by the roughness factor "n" in the Manning formula, increases as the size of the material becomes larger. The results of these studies have been reported in detail elsewhere[13]. Briefly stated, the roughness values obtained agreed very well with Strickler's [15] value $n = K_{50}^{1/6}/44.4$, where n is the Manning coefficient

[15]Beitrage zur Frage der Geschwindigeckformal und der Rauigkeitszahlen fur Strom Kanaele und geschlossene Leitungen, Mitt. No. 16 des Eidg. Amtes fur Wasserwirtshaft, Bern., 1923, K. Strickler.

and K_{50} is the median sieve size in inches. It should be noted that the median size of the material on the bed was considerably larger than that of the material through which the canal was constructed, due to the washing out of the fine material from between the larger particles. In designing a canal it will therefore be necessary to estimate what the bed composition will be after the fine material has been washed out by the flowing water. As the value of n increases with the 1/6 power of the diameter, high accuracy in determining the diameter is not necessary. A comparison of the roughness of the test sections with the size of the material through which the canals were constructed shows a roughness, $n = K_{25}^{1/6}/39$, where K_{25} is the sieve diameter in inches, of which 25 percent of the material was larger. The canal sections from which these roughness values were obtained were especially uniform, and and for design purposes the roughness in the Manning formula indicated by the relation developed from the San Luis Valley tests probably should be increased by about 15 percent. The equation developed is only applicable to coarse, noncohesive material, where the shear values are high enough to remove the fine material. If the shear values are low, the roughness will be smaller than these relations indicate. A study was also made which showed that the roughness is a function of the ratio of the size of the particle to the hydraulic radius. The data, in general, agreed with an equation.

$$26\, n = \left[\frac{\frac{K_{35}}{32}}{R} \right]^{1/6},$$

where K_{35} is the sieve size of the material forming the bed of the canals, of which 35 percent of the material is larger, R is the hydraulic radius and n is Manning's roughness value.

Determination of Limiting Tractive Forces From Limiting Velocities

The data for critical tractive forces obtained from laboratory experiments are applicable to the case of coarse, noncohesive material, but experience has shown that canals can stand materially higher values of tractive force than that which would just start movement in fine, noncohesive material. For the design of canals in this material, therefore, something more than determinations from laboratory studies is necessary. No laboratory data are available for limiting tractive forces in cohesive material. For both of these cases, it would be very desirable if limiting tractive forces could be determined from observations on actual canals. Although study along these lines for Bureau of Reclamation canals is underway, sufficient information for this purpose has not yet been accumulated.

Until field studies of canals in fine, noncohesive and cohesive materials can be made using the tractive force principle, the only method of determining limiting tractive force values for such canals is from the limiting velocities which these canals will stand. A great deal of information on such velocities has been accumulated. Since velocity is not a completely rational parameter for determining scour, these velocity data are not entirely satisfactory, but by an intelligent utilization of them, valuable information can be obtained for use in scour analysis by the tractive force method. An attempt has therefore been made to analyze the data on permissible velocities in canals, as presented in the available publications, and to determine from the values of limiting velocities given the values of tractive force which they

represent.

The three sources of systematic data on permissible velocities in canals which will be safe against scour which are available are those of Etcheverry, Fortier, and Scobey,[9] and the USSR data[10] on Tables 4-7. The data given by Etcheverry[16] (Table 2) are not related by him to the size of canal. The data by Fortier and Scobey are given in Table 3. They state that the values given are for "a depth of 3 feet or less," and suggest that for greater depths a mean velocity greater by 0.5 foot per second may be allowed. They also state that the values are applicable to canals "with long tangents predominating throughout their length," that for canals in sinuous alignment a reduction of about 25 percent is recommended. These values are for canals which have been "aged" or brought up to capacity gradually over a considerable period. Table 3 also gives values which Fortier and Scobey recommended for use when the water transports colloidal silts.

The USSR data give the permissible values for granular material of various diameters, as shown on Table 4. These values are for a mean depth of 1 meter, and for water carrying less than 0.1 percent of sediment of less than 0.005-mm size. For other mean depths these values can be multiplied by factors as shown in Table 5. The article also states that the permissible velocities of Table 4 can be raised by the following percents for flows containing 0.1 to 2.5 percent of sediment less than 0.005-mm diameter; sand 25-65 percent; gravel 10-45 percent; pebbles 0-25 percent. For cohesive material the values given for 1 meter mean depth are as shown in Table 6, and the corrections for other depths are given in Table 7.

To convert the values of limiting velocity given in the three articles previously discussed into exactly equivalent values of tractive force, it is necessary to know the size, shape, shear distribution, and energy gradient of the channels to which these values apply. Since these data are not given in the articles, it is necessary to make certain assumptions regarding them. In the following paragraphs, the assumptions used in converting the various values of limiting velocity are discussed.

Fortier and Scobey realized that greater depths permitted higher velocities and therefore specified the depths to which their velocity applied as 3 feet or less. If the tractive force analysis is sound, a single velocity could not apply to a range of depth from 3 feet to zero. It is believed that most of the canals from which the limiting velocity data were derived had depths in the neighborhood of 3 feet, and this depth has therefore been used in the conversion. If the tractive force principle is correct, the value for a 3-foot depth would vary with the width of the canal and the side slopes. For this conversion, a bottom width of 10 feet and side slopes of 1-1/2:1 have been used, as these were believed to represent as closely as can be estimated a mean of the most probable condition of the canals on which the data were obtained. The energy slope of the canals must also be used, and to determine it, use was made of what was believed to be the most probable value of hydraulic roughness for the nature of the material in which the canal was located, with the Manning flow formula. Much of the uncertainty of using values of tractive force obtained in this manner is eliminated if the same values of roughness and formula are used in computing the energy gradient for the canals under study as were used in determining the permissible tractive forces from the permissible velocities. The values of hydraulic roughness used in arriving at the tractive

[16] "Irrigation Practice and Engineering," Vol. II, p.57, B. A. Etcheverry, McGraw-Hill Book Company.

forces are therefore noted. The values of tractive force corresponding to the Fortier and Scobey values of limiting velocity, as computed under these assumptions, are also given in Table 3. Since the use of a single tractive force value provides in a rational manner a larger velocity for greater depths, no attempt was made to consider the less rational Fortier and Scobey correction for greater depths.

Since the Etcheverry data included no information on size, shape, or side slope of the channels, the same assumptions were made somewhat arbitrarily in converting it as were made in the case of the Fortier and Scobey data. The values of tractive force corresponding to the limiting velocities given by Etcheverry are also given in Table 2.

The permissible velocities of the USSR data are for an average depth of 1 meter. These have been converted into tractive forces assuming the same bed width-depth ratio as assumed for the data from other authorities. Their corrections for other depths are such that practically the same values of tractive force would be obtained if these other depths of flow had been used in estimating the equivalent tractive forces.

Three Classes of Material in Which Canals are Constructed

In designing canals that will be free from scour while carrying relatively clear water, one of the most important factors is the material through which the canal passes. These materials fall into three classes, each of which requires a different method of analysis. These three classes are: (1) coarse, noncohesive material, (2) fine, noncohesive material, and (3) cohesive material.

For the design of canals in coarse, noncohesive material, one must consider not only the limiting tractive force on the bottom but also the action of the particles in rolling down the sloping canal sides. This requires an analysis of the combination of the rolling effect with the longitudinal force of the flowing water, as previously pointed out, and involves the angle of repose of the material. The distribution of the tractive forces on the perimeter of the canal must also be considered. Since the hydraulic roughness of canals in this class varies widely with the size of the particles of the material involved, the roughness factor also is important.

Where the canal is constructed in cohesive material, the particles are prevented from rolling down by cohesion, and hence, the rolling down part of the analysis is not applicable. The design, therefore, involves only the distribution of the tractive force for material in which the canal is constructed. In these canals the hydraulic roughness is not a function of the particle size but rather of the surface irregularities on the banks and usually of the ripple formations on the bed.

Canals in fine, noncohesive material are intermediate between the other two classes. In this class the effect of small amounts of cohesive sediment in the water or in the material through which the canal flows becomes important.

Limiting Tractive Forces in Canals in Coarse, Noncohesive Material.

The material for determining the limiting value of tractive force for use in design of channels in coarse, noncohesive materials consists of the data obtained from the San Luis Valley canals and the results of the determinations of limiting tractive force obtained by computation from limiting velocities, as

given by Etcheverry, Fortier, and Scobey, Nuernberg Kulturamt, and the USSR article. Of these, the studies made on the San Luis Valley canals are most detailed and complete. These latter results are shown on Figure 3. The line A on this figure represents the relation: tractive force in pounds per square foot equals 1 2 the diameter in inches of a particle such that 25 percent of the material in which the canals were constructed is coarser.

Since most of the observations fall either above or very close to this line, it is believed that it probably represents very nearly the true value for limiting tractive force in canals in such material. It is believed, however, that it does not contain sufficient factor of safety for use in design and a value of limiting tractive force in pounds per square foot equal to 0.4 the diameter in inches for the size for which 25 percent of the materials is larger as shown by line B is therefore tentatively recommended for design.

For metric units a similar relation can be used. It is: the tractive force in kilograms per square meter is equal to 0.8 the size in centimeters. This relation differs only 4 percent from the one given in English units.

As these relations were determined on straight canals, its use should be limited to such conditions. For curve canals lower values of tractive force should be used.

Figure 3 was developed in material having a specific gravity of 2.56. If used for materials with appreciable different specific gravities, the tractive forces for a given size as indicated by the diagram must be multiplied by the ratio of the unit weight of the other material submerged to the unit weight of material having a specific gravity of 2.56 when submerged. In the case of porous material, the unit weight with voids filled with water should be used.

The justification of using a direct relation between the diameter of the 25-percent larger size and the tractive force is believed to be amply justified by the evidence obtained from the study of critical tractive force investigations, which show that the general trend of all the data obtained is close to this relation.

In canals designed with this relation, some of the finer material on the banks and bed when first constructed will be moved downstream, uncovering coarser particles which will protect the bed and banks. If this movement is likely to produce undesirable effects, measures to meet this situation will be required. For example, this material moving down a power canal might erode the machinery, and steps to prevent it would be necessary till all the movable material is washed out and stability is attained.

For the design of canals, it is necessary to combine the relations shown by the line on Figure 3 with the effect of the side slopes and of the tractive force distribution on the perimeter of the canal. The method of effecting this combination can best be presented in the form of an example. Suppose that a canal is proposed through slightly angular material, 25 percent of which is 1 inch or over in diameter, and that the canal water section has a 10-foot bottom width, 5-foot depth, and side slopes 2:1. The ratio of bed width to depth is therefore 2. The maximum tractive force on the bottom for a trapezoid with $B/D = 2$ and 2:1 side slopes is shown by Figure 2 to be $0.89wDS$. No motion will occur on the bottom if this $0.89wDS$ does not exceed the limiting value for the material in which the canal is constructed. This limiting tractive value for material, 25 percent of which is over 1 inch in diameter, is shown by Figure 3 to be 0.40 pound per square foot. The limiting longitudinal slope for the canal is, therefore, $S = 0.40 \div 0.89wD$, where $w = 62.5$ lb cu ft and $D = 5$ feet. This limiting slope for movement on the bottom is therefore 0.00144.

To be stable on the sides of the channel the limiting tractive forces must be less than would be safe on a level bottom, by an amount which depends on the side slope of the canal and the angle of repose of the material. The safe angle of repose of slightly angular material of 1-inch diameter is shown by Figure 6 to be 36^0. For side slopes of 2:1 and an angle of repose of 36^0, Figure 4 shows that the safe tractive force on the side slope would be 0.64 of that on a level bottom, or for this case 0.64 x 0.40 = 0.26 lb/sq ft. The maximum tractive force on the sides of a trapezoid with B/D = 2 and side slopes 2:1 is shown by Figure 1 to be 0.76wDS. The longitudinal canal slope required to produce the limiting tractive force on the sides is, therefore, S = 0.26/0.76wD = 0.00108. Since this limiting longitudinal slope is smaller for the sides than for the bottom, the former would control and the canal should not be built with a slope of more than 0.00108.

Limiting Tractive Forces for Canals in Fine, Noncohesive Material.

Based on a consideration of all of the available data, it is believed that the best recommendation which can be made at this time for canals constructed in fine, noncohesive material are those given in Table 8. The comparison of these with most of the data available is shown in Figure 7.

The tentatively recommended values for clear water were selected largely to agree with the Fortier and Scobey value, and conform to the general trend. They are somewhat higher than the USSR values for clear water. The curve of the latter contains a peculair break of curvature at the 1.0-mm size, but no explanation of this was given in the article. The values recommended are slightly above the Straub values of critical tractive force, which were based on laboratory and stream observations.

The values of limiting tractive force tentatively recommended for canals carrying water containing a high content of fine sediment are considerable higher than for clear water, and are based largely on Fortier and Scobey's value for canals in fine sand carrying colloidal silts but they also conform well with Schoklitsch's value for canals in sand. Since "high content of fine sediment" would be interpreted differently by each person, depending on his experience, it is desirable to define this more closely. For high content of fine sediment the author had in mind water streams that would contain a load of 2 percent or more of silt and clay sizes, on an average of two or three times a year, but would carry only a low content of sand. Unfortunately, sufficient information is not available to set limits for the allowable sand content. Where much sand is carried, this method of analysis is not applicable.

Since these data were largely obtained from limiting velocities for straight canals, the values recommended are also for such alignment, and for crooked canals lower values must be used.

The tentatively recommended values for canals carrying a low content of fine sediment in the water are intermediate between the case of clear water and that of heavy sediment load. It conforms, in general, with the values given by the Nuernberg Kulturamt (N.K.). By low content of fine sediment, the author has in mind a content of silt and clay sizes reaching about 0.2 percent on the average two or three times a year. The sand content should be very low.

It will be seen that the values tentatively recommended for clear water are very much higher for the fine sand than the critical tractive forces indicated from flume tests. The general order of magnitude of the values in the two cases appears to be well established and some explanation of the difference is

therefore needed. This difference is probably due to the fact that clear water such as is used in the laboratory is seldom obtained in natural channels, and the sand through which the canals pass is rarely as clean as that used in the laboratory, but usually has at least a little binder material in it. The growth of minute organisms in the water may also be a factor. Another factor is that a slight movement of material in a canal would not cause it to be considered unstable, as it would probably not have objectionable results.

The higher values allowable with fine suspended sediment are probably largely due to the cementing effect of this material on the banks and bed of the channel. In the case of high fine sediment content it is probably partly due also to the fact that with a silt and clay size content of 2 percent, some sand would also be carried, and this would reduce the effect of the scour on the bed.

The size specified for the fine, noncohesive material is the median size, or size of which 50 percent of the weight is larger, while the size specified for the coarse, noncohesive material is the size of which 25 percent is larger. The median size is used for the fine material because this is the usual criterion for describing such material. In the coarse material only the coarser material remains to protect the bed and banks, and the 25-percent larger size defines this large material much better than the median size. The use of the two systmes introduces an uncertainty in the vicinity of the 5-mm size, which was somewhat arbitrarily selected as the division between these classifications. For example, a material in which the part larger than 5-mm size falls between 25 and 50 percent would be included in both the coarse and fine classification. It is believed, however, that this difficulty can be removed by using whichever classification gives the lower tractive force.

Where very clear water is used, it is probable that the rolling down effect, previously mentioned, will be effective, but information on the angle or repose of such material is meager. It is believed that for clear water flowing in fine, noncohesive material, flat side slopes are necessary. Where the water carries a low or a high content of fine sediment, and a period of aging will occur before the canal discharges reach the design capacity, the deposits of fine material on the banks will prevent the rolling down from occurring. An exception to this occurs where the canal is below the ground-water level, and the water flowing into the canal through the banks prevents the deposition of the fine sediment.

Limiting Tractive Forces in Cohesive Materials

For the design of canals in cohesive material the only data on safe tractive forces available are those obtained by converting limiting velocities as given by Etcheverry[16], Fortier and Scobey[9], and the USSR data to the values of tractive force. Studies are underway to evaluate the experience with the canals of the Bureau of Reclamation projects, from which it is hoped more complete information can be obtained, but to date a digest and synthesis of the available material into a systematic procedure has not been accomplished. Until this is done, canal designers wishing to use tractive forces in their designs will have to select limiting values of tractive force from an examination of the data based on the conversion of limiting velocities to tractive force given in Tables 2, 3, and 6.

In canals in cohesive material the effect of the distribution of tractive forces, as shown in Figures 1 and 2, should be considered, but the rolling-down effect is not applicable.

Canals Carrying Heavy Sediment Loads

Although little quantitative study has yet been given in the Bureau of Reclamation studies to the case of canals carrying heavy sediment loads, it is expected that work will be carried on in this field in the future. It is believed, however, that the basic principles involved in the design of such canals have been developed. Briefly stated, they are as follows: If appreciable quantities of sediment are introduced into a canal with the water, for the canal to be stable, the conditions in it must be such that this sediment is carried through the canal without deposit. In other words, the canal must be able to transport the sediment which is introduced into it. Usually the greatest difficulties are experienced in transporting the sand and coarser sizes of material. Since most of this material travels near the bed, a stable channel must have sufficient shear acting on the bed to transport this load. At the same time, however, the shear on the sides must not be great enough to scour the sides. Also the shear on the bottom must not be enough greater than that required to transport the sediment so that scour of the original material of the bed results.

If large quantities of fine material are carried, the shear must be such throughout the section to keep this material from depositing, without being sufficient at any point to scour the original material of the bed and banks. Where large quantities of both fine and coarse material are carried, the shear on the bed must be sufficient to cause the transportation of the coarse material, and sufficient on the banks to prevent the deposition of the fine material, but must not exceed that required to prevent deposition sufficiently to produce scour.

It will thus be seen that the laws of transportation of sediment are an important factor in the stable channel problem. Considerable progress in determining these laws has been made in recent years, but much still remains to be accomplished. Probably the most advanced work along this line in recent cent years is the work of Einstein[17].

Effects of Bends

Perhaps the phase of stable channel design regarding which least is known is the effect of bends. It has long been evident that sinuous canals scoured more easily than straight ones, but almost nothing of a quantitative nature is available on this effect. A study of the scour at bends, both in the laboratory and in the field, is a part of the program of stable channel studies being carried on by the Bureau of Reclamation.

Canals of the Bureau of Reclamation have sometimes been designed to limit the radius of bends to six times the water surface width. On other canals a limit of 15 times the water depth has been used. A number of other suggestions have been made[18, 19]. There is great need, however, of more accurate knowledge on which to base design procedures.

The scour in bends can be reduced by lowering the velocity of flow, which may be accomplished by using larger canal areas, but this results in an

[17] "The Bed-Load Function for Sediment Transportation in Open Channel Flows," H. A. Einstein, U. S. Department of Agriculture, Technical Bulletin No. 1026, 1950

[18] Irrigation Practice and Engineering, Vol. II, Etcheverry, p. 39

[19] Bishop, <u>Transactions ASCE</u>, Vol. 74, December 1911, p.188

increased cost. It will often be more economical to allow scour to start in canals and stop it by protecting the banks at the points where scour occurs, rather than use the larger cross sections necessary to insure that no scour will take place. With the present knowledge, it is impracticable to place protection at the bend in advance as this would lead in many cases to protection where it is not needed.

It is hoped that the publication of this progress report will bring out some discussion on the effect of bends. Since this experience is likely to be in terms of velocity, however, it will be necessary to convert it into tractive force. Data will be more easily compared if some basis of comparison is given. For this purpose the comparison of the velocities and tractive forces in straight canals and canals of different degrees of sinuosity given in Table 9 can be used. In order to define more closely the meaning of these various degrees of sinuosity, the following may be useful: Straight canals have straight or very slightly curved alignment, such as are typical of canals in flat plains. Slightly sinuous canals have a degree of curvature which is typical of slightly undulating topography. Moderately sinuous canals have a degree of sinuosity which is typical of moderately rolling topography, and very sinuous canals have a condition of curvature which is typical of canals in foothills or mountainous topography.

The values in Table 9 compare the permissible tractive forces and velocities in canals with various degrees of curvature with those in straight canals. It will be seen that the tractive force values have a wider range than the corresponding mean velocities. These values are, in the writer's opinion, as close to the true values as it is possible to come, at the present time, with the data available to him. Because the values are based so largely on judgment, however, rather than on observed data, one does not feet justified in making them as a recommendation.

Nonscouring Canals of Minimum Excavation and Width

In studying trapezoidal canals, considering the distribution of tractive force on the sides and bottom and the rolling-down action of the material on the sides, as pointed out previously in this paper, it was found that the tractive forces close to the limiting value occurred over only a part of the perimeter of the canal, and on most of the perimeter forces less than this amount acted. It was believed that a section on which the limiting tractive force acted over the entire perimeter might have interesting properties, and the mathematical requirements of such a section were therefore set up and its shape determined. Study showed that within the limitations of the approximating assumptions used, this section had other important properties, in addition to the property of impending motion over the entire periphery. Under certain conditions, the obtaining of these properties will make possible substantial savings. Further studies were therefore made to refine the accuracy of the determination. In the following paragraphs, the principal results of this study are given.

In the section developed, the material on the entire wetted perimeter is in a state of incipient motion, and the side slopes above the water line are at the angle of repose. Under these conditions it was found that this section has also interesting properties for a channel in a coarse, noncohesive material. For material with a given angle or repose and for a given discharge, this section provides not only the channel of minimum excavation, but also

the channel of minimum top width, maximum mean velocity, and minimum water area.

The shape of the channel is dictated by the following five assumptions: (1) at and above the water surface, the side slope is at the angle of repose of the material; (2) at points between the center and edge of the channel the particles are in a state of incipient motion, under the action of the resultant of the gravity component of the particles submerged weight acting down the side slope and the tractive force of the flowing water; (3) at the center of the channel the side slope is zero and the tractive force alone is sufficient to cause incipient motion; (4) the particle is held against the bed by the component of the submerged weight of the particle acting normal to the bed; and (5) the tractive force on any area is equal to the component of the weight of the water above the area in the direction of flow. Under Assumptions 1, 2, and 3 the particles on the entire perimeter of the canal cross section are in a state of impending motion.

For the fifth assumption to be true, there can be no transfer of force horizontally between adjacent currents moving at different velocities in the section. This is, of course, not the case, as the faster moving water near the center of the channel tends to carry along the slower moving water near the sides. As part of this study, however, a detailed mathematical treatment of this problem was carried out, which indicated that for the shape of channel which would be likely to be encountered in practice, the departure of the approximate assumption from the true conditions would have very little effect on the shape of the section.

Space limitations prevent the development of the form of this channel in this paper, but it has been described in separate reports[3,20]. For a given discharge and longitudinal canal slope in a material of given angle of repose and having a known limiting tractive force, the solution gives the shape and dimensions of the channel which will have the properties previously discussed. It is also possible to introduce factors of safety, so that the material will have the same factor of safety against motion at all parts of the perimeter of the water and above water section.

Future Studies

The program of studies undertaken by the Bureau of Reclamation for the improvement in canal design procedures is well underway but a great deal of work remains before its completion.

The following studies are planned: Additional studies of limiting tractive forces along four lines: (1) laboratory tests of graded materials, to study the shingling effect of the removal of the finer fractions of a graded material, to determine safe values of design for such mixtures of sizes and the amount of material moved away before stability is obtained. Also, a study of the effect of the shape of the particles on the critical tractive force. (2) Studies of available data in the literature and field observations to obtain better knowledge of the limiting shear on cohesive material and on the material formed by the deposit of fine sediment carried in suspension by the canals. (3) A field study of the experience with scour in Bureau of Reclamation canals, when expressed in terms of tractive force; and (4) A study of the scour

[20] "Stable Channel Profiles," R. E. Glover and Q. L. Florey, Bureau of Reclamation Hydraulic Laboratory Report No. Hyd-325

resistance of clay soil and its relation to the properties of clay involved in its structural stability.

Further studies of shear distribution are also planned, composed of both laboratory and field investigation. The laboratory work should consist of measurements of shear distribution on the periphery of trapezoidal channels and the corresponding velocity distribution, for channels both of equal and unequal roughness on the sides and bottom. Field studies of velocity distribution in similar channels would also be made to compare with the laboratory studies and thus obtain correlation of model and prototype shear distribution. A check would be made on the assumption that the shear distribution on channels of similar cross section would be similar. A study both in the field and laboratory is also planned of the possibility of measuring the shear at any point on the canal perimeter by means of measurements of the velocity gradients at these points.

Model studies of trapezoidal channels on coarse material are contemplated to establish the degree of reliability of the analysis of the rolling-down effect on the side slopes developed in this report. Further studies of the angle of repose of material of different sizes, shapes, and also on graded material of various sizes are also included in the program. Particularly, attention would be given to the larger sizes of material to allow for removal of the arbitrary limitations suggested in this report.

Laboratory and field studies of the laws of sediment transportation would also be carried on to determine better methods of estimating the quantity of various sizes of sediment carried by canals. Work along this line is now in progress under the Hydrology Branch of the Bureau.

A study is also planned to try to correlate and compare the canal-analysis methods developed in India and Pakistan with the methods developed in this paper in order to obtain any advantages there might be from a combination of the methods or data.

An investigation of the effect of bends is included in the program, both in the laboratory and in the field. The laboratory study would consist of experiments with bands of various radii, central angle, bottom width, side slopes, and velocities to study the scouring effects under various conditions. The possibilities of spiraling curves and superelevation of the bed would also be considered. The field study would consist of observations on bends in canals which have produced scour, to obtain data on the conditions which cause trouble in actual cases.

A laboratory study is programmed to establish the degree of reliability of the analysis of the shape of the channel of impending motion throughout the sides and bottom. It is apparent that it will take a long time to complete this program. The principal purpose in listing these studies is to show the information that is still needed to obtain a satisfactory design method. The assistance of anyone interested in working on any of these problems would be of value.

Summary

The methods of design suggested in this report are based on the results of the studies described herein and are largely the author's interpretation of those results. Since they have very recently been completed, they do not represent experience based on a long period of use in canal design. Time has not been available to secure a thorough discussion of them from the many qualified persons in the Bureau of Reclamation, and no formal action on them

by the Bureau has been taken, although the general reaction to these suggestions seems to be favorable and the use of tractive force by Bureau personnel in place of velocity as a parameter of design is rapidly spreading. Some of the processes seem to be well established, and others, because of lack of data, are based on less well-established foundations. In all cases, the author has attempted to indicate so fas as space limitations permitted the extent of the supporting information. The need of further studies to check and perfect the methods proposed herein is evident and this paper should be considered, therefore, to be of the nature of a progress report. It is the author's belief, however, that the results described and the methods proposed herein represent progress toward better stable channel design, and that their use for design in their present form is amply justified until further studies can be made to perfect them.

Acknowledgments

The studies described in this paper were the work of a large group of men on the staff of L. N. McClellan, the Chief Engineer of the Bureau of Reclamation. The number who have taken part in these studies is so large that it is practicable to acknowledge only those who made the more important contributions to it.

Most of the mathematical work of this study, including that on the analysis of the most efficient channel and the shear distribution on the perimeter of canals, was carried on by R. E. Glover, Research Engineer, assisted by F. E. Swain, R. G. Conard, and Q. L. Florey. The membrane analogy studies were carried out by O. J. Olsen under the direction of D. McHenry, who also introduced the method of finite difference analysis. A. C. Carter carried on the studies of shear distribution in canals based on velocity distribution, on limiting tractive forces, angles of repose, and effect of side slopes. O. S. Hanson investigated the hydraulic roughness of canals and angles of repose. E. J. Carlson carried on most of the studies of the San Luis Canal data, and also studied hydraulic roughness, angles of repose, and effect of side slopes. C. R. Miller also worked on the San Luis Valley canal studies. R. P. Verma assisted on the velocity distribution studies. These investigations were largely carried on as a part of the work of the Hydraulic Laboratory Section, which is directed by H. M. Martin with C. W. Thomas in charge of this part of the work. The staff of the San Luis Valley Project office carried on the canal measurements in that valley. Helpful advice was also received from R. E. Glover, D. J. Hebert, C. R. Burky, I. B. Hosig, P. W. Terrell, H. G. Curtis, and N. L. Govinda Rao.

Table 1

TRACTIVE FORCE DISTRIBUTION IN
TRAPEZOIDAL CHANNELS
In terms of wSD**

Method		Membrane analogy												Analytical	Finite difference		
Shape of channel		Trapezoidal						V-notch					Rectangular				
Side slope ss		2:1	2:1	2:1	1-1/2:1	1-1/2:1	1-1/2:1	2:1	1-1/2:1	1:1	2/3:1	1/2:1	0:1	0:1	0:1	0:1	0:1
Bottom width b		2	4	8	2	4	8	0	0	0	0	0	2	2	2	4	1
Side boundary points, vertical distance above bottom	1.0	0	0	0	0	0	0	0	0	0	0	0	*0.680	*0.686	*0.686	*0.744	*0.468
	0.9	0.130	0.130	0.120	0.160	0.190	0.160	0.130	0.160	0.230	0.270	0.275		.677	.676	.740	
	0.8	.250	.260	.240	.320	.330	.300	.260	.290	.350	.350	.320	.660	.654	.664	.724	.460
	0.7	.380	.380	.360	.450	.450	.420	.380	.400	.440	*.375	*.325		.625	.636	.700	
	0.6	.500	.490	.470	.550	.570	.530	.470	.480	.470	.370	.305	.620	.597	.610	.664	.435
	0.5	.600	.590	.580	.620	.650	.610	.550	.530	*.480	.350	.275		.566	.560	.610	.415
	0.4	.680	.680	.660	.690	.710	.690	.610	.560	.470	.320	.235	.500	.523	.510	.550	.385
	0.3	.730	.740	.730	.730	*.750	.740	*.650	*.565	.440	.270	.190		.449	.436	.476	.342
	0.2	*.760	*.770	*.770	*.735	.740	*.760	.640	.520	.350	.190	.130	.320	.335	.340	.360	.278
	0.15	.760	.765	.760	.720	.710	.710	.600	.480								.235
	0.1	.740	.750	.720	.670	.670	.630	.550	.400	.230	.110	.065	.180	.180	.200	.220	.180
	0.05	.670	.660	.640	.530	.590	.520	.440	.290	.130			.100				.110
	0.025									.070			.060				
Bottom boundary points horizontal distance from outside edge toward center	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	0.025												.060				
	0.05												.100				.110
	0.1	.700	.730	.720	.660	.640	.660						.180	.211	.200	.220	.180
	0.2	.770	.800	.770	.730	.740	.730						.320	.345	.340	.360	.275
	0.3	.800	.840	.810	.780	.790	.780							.436	.436	.470	.332
	0.4	.830	.870	.840	.810	.830	.820						.500	.507	.510	.556	.362
	0.5													.563	.560	.624	*.372
	0.6	.870			.850								.620	.605	.610	.684	
	0.8		.930	.920		.910	.910						.660	.658	.664	.770	
	1.0	*.890			*.890								*.680	*.675	*.686	.830	
	1.2		.950			.950										.870	
	1.6		.960	.970		.965	.960									.920	
	2.0		*.970			*.970										*.936	
	2.4			.980			.980										
	4.0			*.990			*.990										

*Maximum values, bottom and side.

**w = unit weight of water
S = energy gradient
D = depth of flow

Table 2

COMPARISON OF ETCHEVERRY'S MAXIMUM ALLOWABLE VELOCITIES WITH TRACTIVE FORCE VALUES

Material	Value of Manning's n used	Velocity ft/sec	Tractive force lb/sq ft
Very light pure sand of quick-sand character	0.020	0.75-1.00	0.006-0.011
Very light loose sand	.020	1.00-1.50	0.011-0.025
Coarse sand or light sandy soil	.020	1.50-2.00	0.025-0.045
Average sandy soil	.020	2.00-2.50	0.045-0.070
Sandy loam	.020	2.50-2.75	0.070-0.084
Average loam, alluvial soil, volcanic ash soil	.020	2.75-3.00	0.084-0.100
Firm loam, clay loam	.020	3.00-3.75	0.100-0.157
Stiff clay soil, ordinary gravel soil	.025	4.00-5.00	0.278-0.434
Coarse gravel, cobbles and shingles	.030	5.00-6.00	0.627-0.903
Conglomerate, cemented gravel, soft slate, tough hardpan, soft sedimentary rock	.025	6.00-8.00	0.627-1.114

Table 3

COMPARISON OF FORTIER AND SCOBEY'S LIMITING VELOCITIES
WITH TRACTIVE FORCE VALUES

Straight Channels After Aging

Material	n	For clear water		Water transporting colloidal silts	
		Velocity ft/sec	Tractive force lb/sq ft	Velocity ft/sec	Tractive force lb/sq ft
Fine sand colloidal	0.020	1.50	0.027	2.50	0.075
Sandy loam noncolloidal	.020	1.75	.037	2.50	0.075
Silt loam noncolloidal	.020	2.00	.048	3.00	0.11
Alluvial silts noncolloidal	.020	2.00	.048	3.50	0.15
Ordinary firm loam	.020	2.50	.075	3.50	0.15
Volcanic ash	.020	2.50	.075	3.50	0.15
Stiff clay very colloidal	.025	3.75	.26	5.00	0.46
Alluvial silts colloidal	.025	3.75	.26	5.00	0.46
Shales and hardpans	.025	6.00	.67	6.00	0.67
Fine gravel	.020	2.50	.075	5.00	0.32
Graded loam to cobbles when noncolloidal	.030	3.75	.38	5.00	0.66
Graded silts to cobbles when colloidal	.030	4.00	.43	5.50	0.80
Coarse gravel noncolloidal	.025	4.00	.30	6.00	0.67
Cobbles and shingles	.035	5.00	.91	5.50	1.10

Table 4

USSR DATA

ON PERMISSIBLE VELOCITIES FOR NONCOHESIVE SOILS

Material	Particle diameter mm	Mean velocity ft/sec
	0.005	0.49
Silt		
	0.05	0.66
Fine sand		
	0.25	0.98
Medium sand		
	1.00	1.80
Coarse sand		
	2.50	2.13
Fine gravel		
	5.00	2.62
Medium gravel		
	10.00	3.28
Coarse gravel		
	15.0	3.94
Fine pebbles		
	25.0	4.59
Medium pebbles		
	40.0	5.91
Coarse pebbles		
	75.0	7.87
Large pebbles		
	100.0	8.86
Large pebbles		
	150.0	10.83
Large pebbles		
	200.0	12.80

Table 5

USSR CORRECTIONS OF PERMISSIBLE VELOCITY FOR DEPTH

Noncohesive Material

	Average depth						
Meters	0.30	0.60	1.00	1.50	2.00	2.50	3.00
Feet	0.98	1.97	3.28	4.92	6.56	8.20	9.84
Correction factor	0.8	0.9	1.00	1.1	1.15	1.20	1.25

Table 6

USSR LIMITING VELOCITIES AND TRACTIVE FORCES IN COHESIVE MATERIAL

	Compactness of bed							
Descriptive term	Loose		Fairly				Very	
Descriptive term	loose		compact		Compact		compact	
Voids ratio	2.0-1.2		1.2-0.6		0.6-0.3		0.3-0.2	
Principal cohesive	Limiting mean velocity ft/sec and limiting tractive force lb/sq ft							
Material of bed	Ft/sec	Lb sq ft	Ft sec	Lb sq ft	Ft sec	Lb sq ft	Ft sec	Lb sq ft
Sandy clays (sand content less than 50 percent)	1.48	0.040	2.95	0.157	4.26	0.327	5.90	0.630
Heavy clayey soils	1.31	0.031	2.79	0.141	4.10	0.305	5.58	0.563
Clays	1.15	0.024	2.62	0.124	3.94	0.281	5.41	0.530
Lean clayey soils	1.05	0.020	2.30	0.096	3.44	0.214	4.43	0.354

Table 7

USSR CORRECTIONS OF PERMISSIBLE VELOCITY FOR DEPTH
Cohesive Materials

	Average depth							
Meters	0.3	0.5	0.75	1.0	1.5	-2.0	2.5	-3.0
Feet	0.98	1.64	2.46	3.28	4.92	-6.56	8.20	-9.84
Correction factor	0.8	0.9	0.95	1.0	1.1	-1.1	1.2	-1.2

Table 8

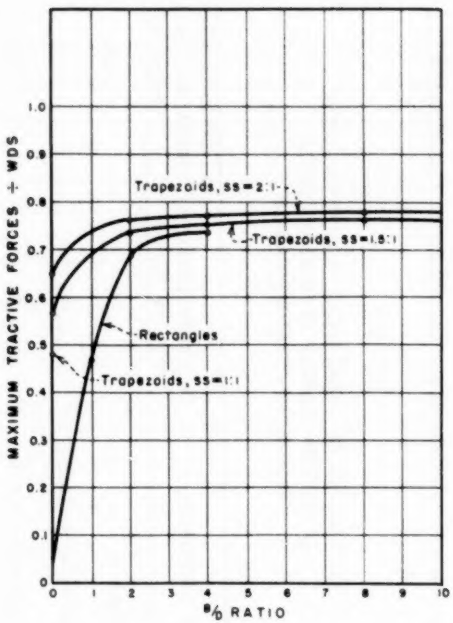
TENTATIVELY RECOMMENDED LIMITING VALUES OF TRACTIVE FORCE
FOR CANALS IN FINE, NONCOHESIVE MATERIAL

Median size of material mm	Limiting tractive force lb/sq ft		
	Clear water	Light load of fine sediment	Heavy load of fine sediment
0.1	0.025	0.050	0.075
0.2	.026	.052	.078
0.5	.030	.055	.083
1.0	.040	.060	.090
2.0	.060	.080	.110
5.0	.140	.165	.185

Table 9

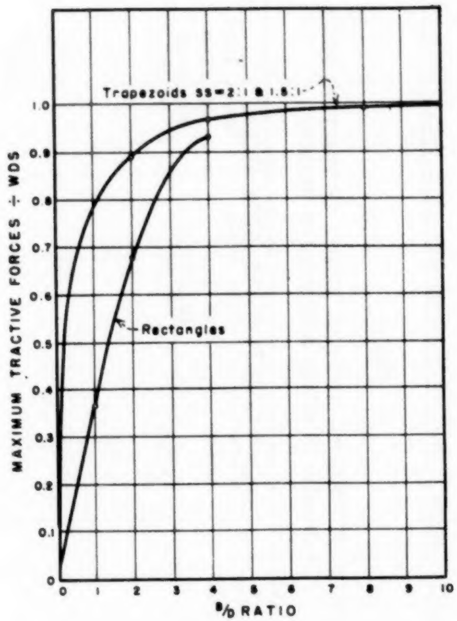
COMPARISON OF PERMISSIBLE TRACTIVE FORCES
IN SINUOUS CANALS WITH PERMISSIBLE
VALUES IN STRAIGHT CANALS

Degree of sinuosity	Relative limiting tractive force	Corresponding relative limiting velocity
Straight canals	1.00	1.00
Slightly sinuous canals	0.90	0.95
Moderately sinuous canals	0.75	0.87
Very sinuous canals	0.60	0.78



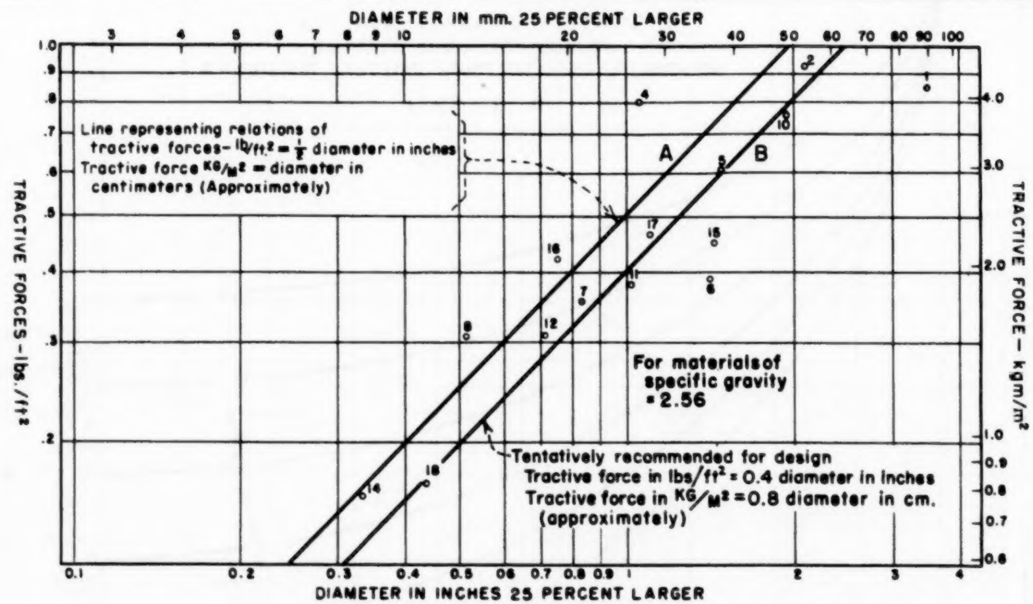
MAXIMUM TRACTIVE FORCES IN TERMS OF WDS
ON SIDES OF CHANNELS

FIGURE 1



MAXIMUM TRACTIVE FORCES IN TERMS OF WDS
ON BOTTOM OF CHANNELS

FIGURE 2



RESULTS OF STUDIES ON SAN LUIS VALLEY CANALS

FIGURE 3

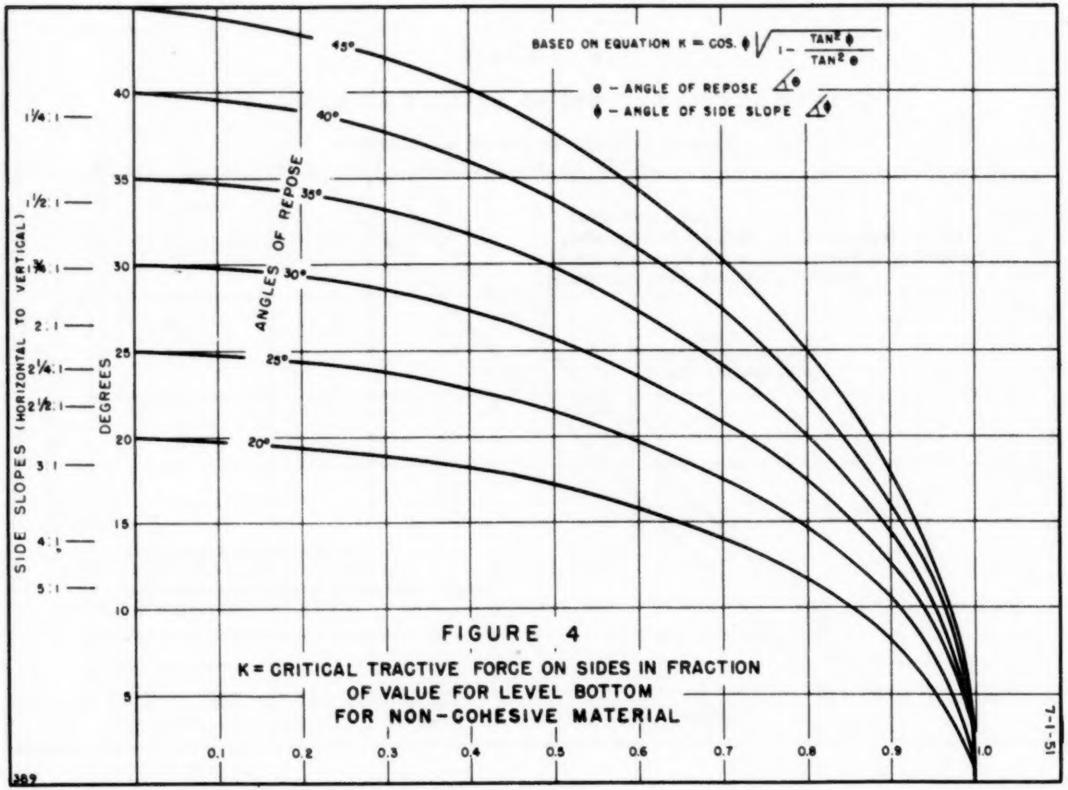
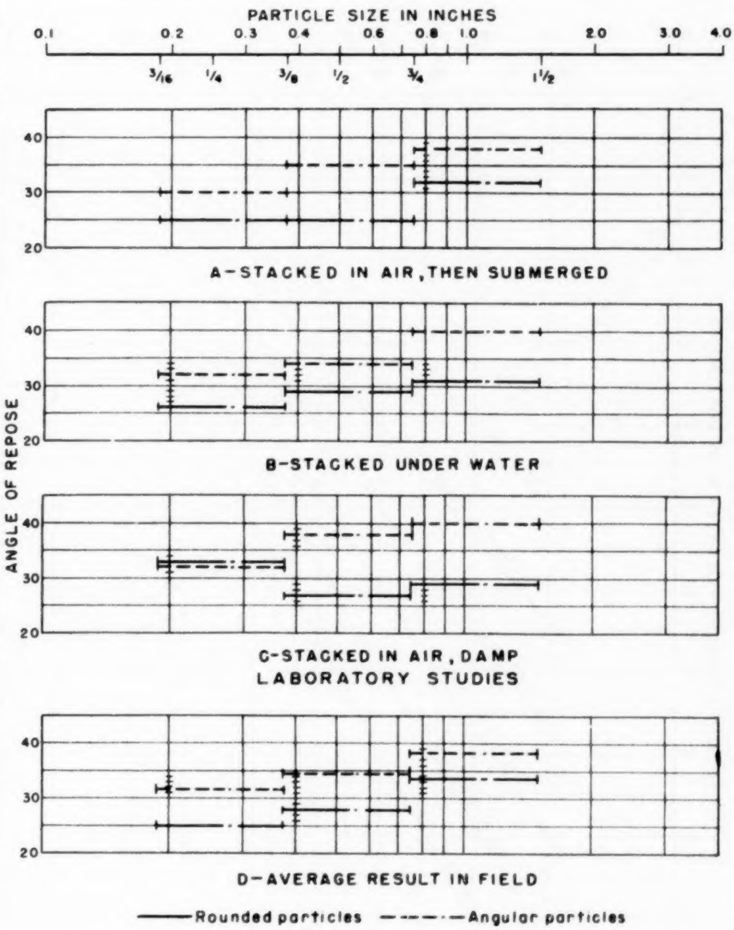


FIGURE 4

K = CRITICAL TRACTIVE FORCE ON SIDES IN FRACTION OF VALUE FOR LEVEL BOTTOM FOR NON-COHESIVE MATERIAL



RESULTS OF OBSERVATIONS ON ANGLE OF REPOSE OF COARSE NON-COHESIVE MATERIAL

FIGURE 5

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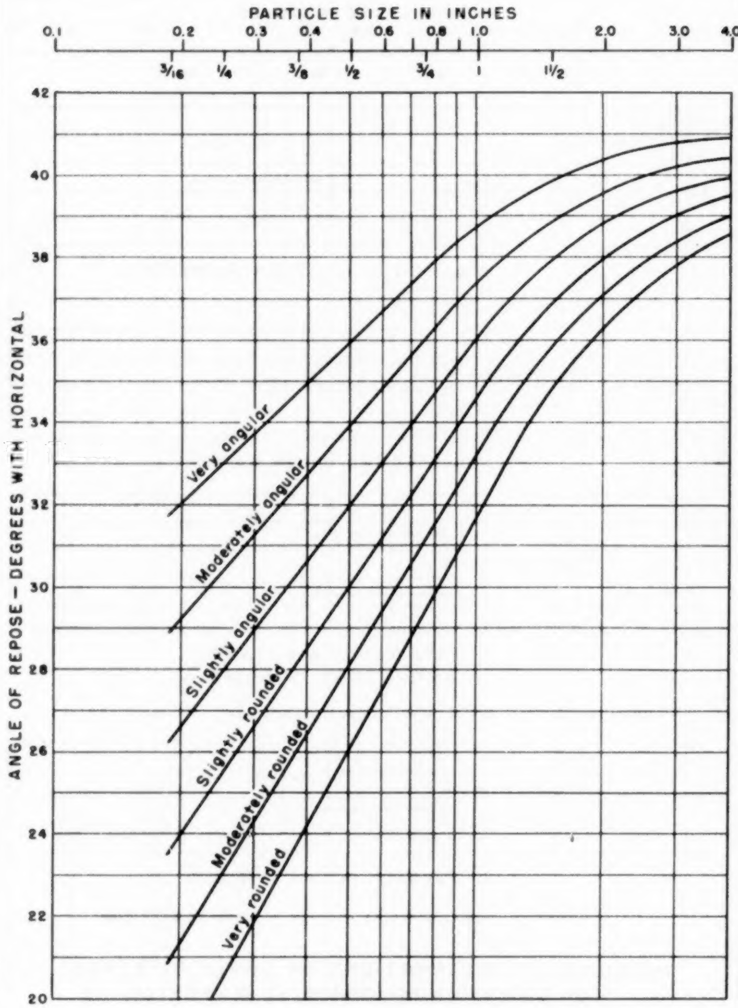

ANGLES OF REPOSE OF NON-COHESIVE MATERIAL

FIGURE 6

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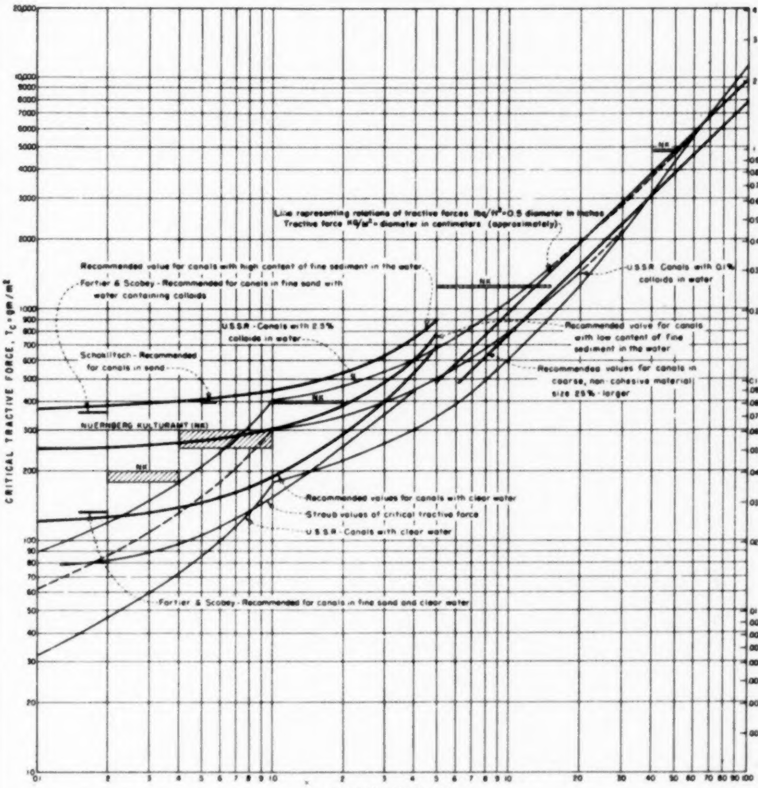

LIMITING TRACTIVE FORCES
RECOMMENDED FOR CANALS

FIGURE 7

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